SEDIMENT DEPOSITION IN HAJI DAM AND SIMULATION OF BED VARIATIONS

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This paper presents a basic analysis of deposition and erosion processes as an important aspect of sediment management in reservoirs. For this purpose, field data from Haji dam reservoir was analyzed to evaluate the mechanism of sediment deposition and its dependence on the hydraulic conditions especially during floods. This study also includes laboratory experiments and numerical computation to assess these processes under different conditions. Regarding the numerical computation, the bed transients in our experiments were better simulated when the Einstein resistance law was used to compute the effective shear stress in the Ashida-Michiue's sediment transport formula, in comparison to the case using the traditional formulation.

Keywords: *sediment management, reservoir capacity recovery, hydraulic flushing, sediment deposition, MacCormack scheme.*

1. INTRODUCTION

Haji dam is a multipurpose dam, which was built 26 years ago, in 1974. Flood control, power generation and water storage are its main functions. Until now, the sediment problem is minor representing no threat for the normal operation of the reservoir.

However, it is desirable at this stage, to initiate the consideration of alternatives to cope with sediment deposition to achieve effective sediment management for the future. For this purpose, it is indispensable to consider the characteristics and spatial distribution of the deposits.

The field data employed for this analysis consisted in longitudinal and transversal cross sections, plan-shape, inflow-outflow hydrographs and sediment size distribution.

2. SEDIMENT DEPOSITION AT HAJI DAM RESERVOIR

Figure 1 shows the reservoir plan-shape. It has a very irregular and meandering geometry. **Figure 2** shows the bed profiles along the deepest locations for different years, illustrating the front growth in the last 25 years.

The process of deposition in Haji dam has two main characteristics: First, the front top set is almost horizontal with a negligible aggradation after 1986 forming a shallow region.

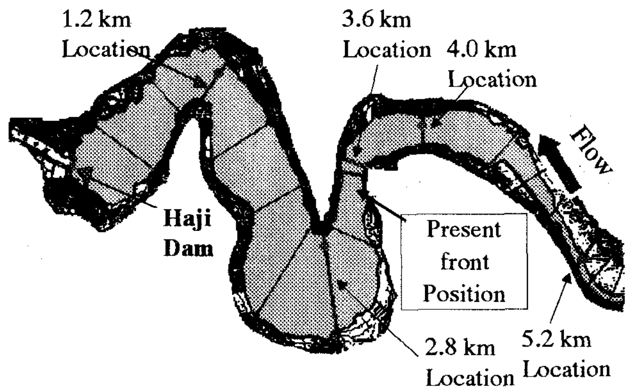

Fig. 1: Plan shape of Yachiyo Reservoir at Haji Dam.

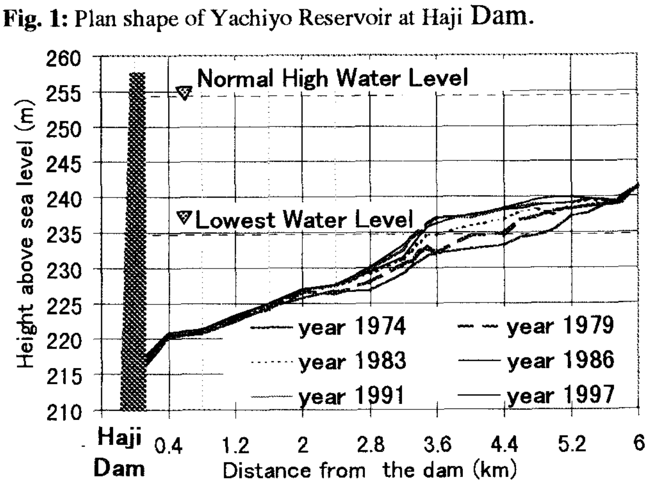

Fig. 2: Longitudinal bed profiles at Yachiyo Reservoir at Haji Dam.

This is due to fact that the sediment has filled up the main channel of the former compound cross section, becoming now single section so that the sediment can spread more. Second, the front has decreased abruptly its displacement rate when reached the kilometer 3.6, location at which the transversal area started to increase significantly thereby diminishing the transport capacity.

In consequence, only silt and clay have deposited from this point toward the dam, as can be seen in **Figure 3**.

Figure 4 relates the annual volumes of sediment deposition and water inflow due to floods. An important correlation is observed. Also, the annual volumes of sediment deposition correlated significantly with other indicators like annual flood frequency and flood magnitude indicating that flooding plays a basic role in the sedimentation process at Haji dam's reservoir.

Regarding the suspended sediment, **Figure 5** shows the annual volumes of sediment deposition due to suspended sediments (grain sizes less than 0.1 mm) and due to the total sediment inflow for a period of six years.

By comparing these values with the flood frequency for each year, it can be seen that for a year with abundant and large floods like in 1997, the deposition of suspended sediment is low as it can pass the dam and continue downstream with the flood.

However, for a year like 1993 or 1995 with relatively few large-scale floods, the deposition due to suspended sediment is predominant. Furthermore, it is observed that the amount of sediment deposition does not vary or even can decrease for years with few or no floods, as can be seen in the years 1994 and 1996.

We can realize that the sedimentation still in early stages and it is not an actual problem; but at this point we are interested on the process of deposition and how the front arrives to its actual and future configurations.

From the plan-shape it can be assumed that the front formed up to now has basically a one-dimensional character due to the small channel width in which it has developed, therefore the sediment can advance in a uniform manner at each section.

However, as the channel width increase and curvature becomes apparent, it is expected that the pattern of sedimentation will be affected significantly by topography features and transversal distribution of velocity so that the front will start deforming accordingly.

To understand better the process of front formation in Haji dam, we carry out laboratory experiments in the straight channel aiming to reproduce at some

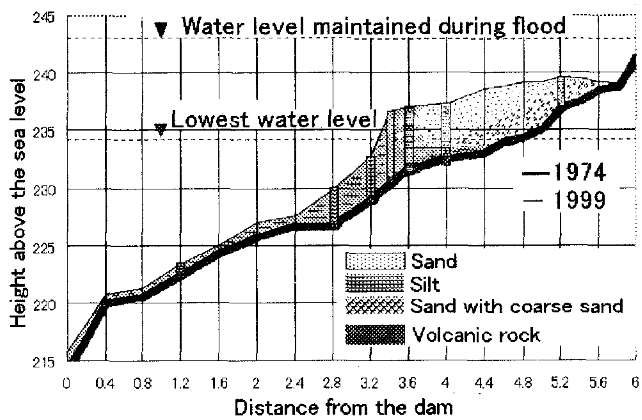

Fig. 3: Longitudinal distribution of sediment sizes in the deposits at Yachiyo Reservoir, Haji Dam.

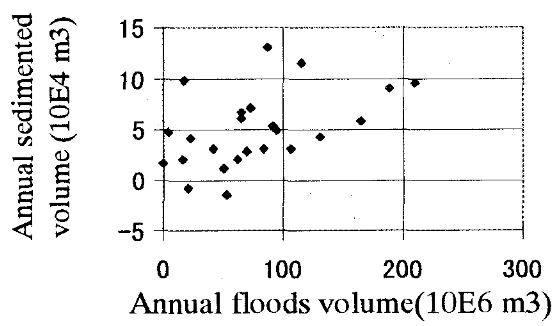

Fig. 4: Relation between floods and deposition in Haji dam reservoir.

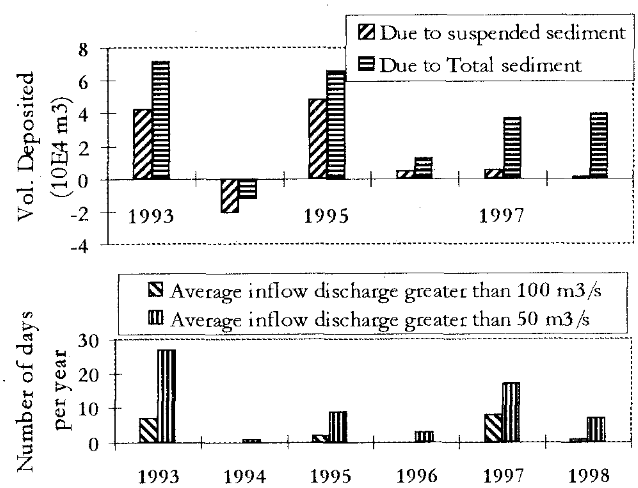

Fig. 5: Flood scale and frequency per year at Haji dam

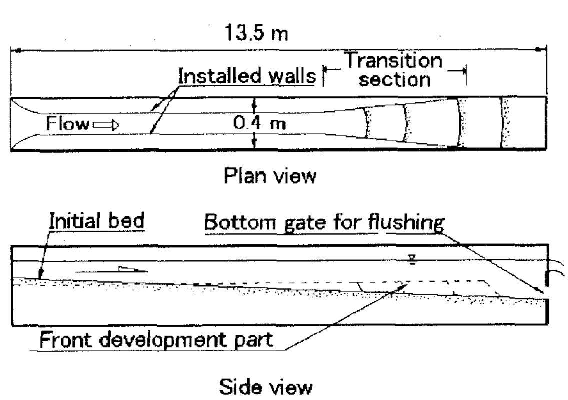

Fig. 6: Schematic sketch for front formation runs in the narrow flume

extent the features of deposition observed in the field by assuming a one-dimensional process.

Also, as a countermeasure for sedimentation, we performed experiments of sediment flushing to evaluate the flushing performance for several depositional patterns.

3. LABORATORY EXPERIMENTS AND COMPUTATION

(1) Experiments with one dimensional character in a narrow flume

The re-circulating straight flume used has the following dimensions: length 13.5, width 0.4 and height 0.5 meters with adjustable slope. At the downstream end, the dam facility with a bottom gate was installed. The bed material used was uniform size silica-sand with D_{50} equal to 0.0008 m and specific gravity of 2.65.

a) Experiments for sediment deposition runs

The channel width varied longitudinally as shown in **Figure 6**, this was to assure suitable sediment movement in the middle and deposition at the downstream part, near the dam.

Regarding the experimental procedure, the bed was initially flat and parallel to the flume floor, the bed started to deform under constant inflow discharge and the water surface elevation controlled by the dam height.

At the upstream end, no sediment supply was done. Therefore degradation occurred in the upper part as the bed began to scour. The effect of the inflow discharge and water surface elevation was examined in the front formation process.

b) Procedure for sediment flushing runs

Different initial bed conditions were employed. In one case an initial flat bed was adopted (run F0), in the others, the bed configuration obtained in the front-formation run was the initial bed condition for the flushing runs (runs F1,F2,F3 and F4), thus being possible to observe the front erosion as the water drawdown progressed.

The run began when the bottom gate was opened manually to allow for water surface drawdown in the vicinity of the dam. This resulted in erosion of the front until the sediments left the channel through the bottom gate. To measure the bed transients, the gate was closed temporarily and later the flushing operation was restarted.

The sediment discharge was collected manually in alternate intervals of 30 seconds for run F0, in the other cases, the cumulative flushed sediment was calculated from the measured bed elevation differences. For these runs, the effect of varying the inflow discharge and the bottom gate elevation in the flushed sediment quantities was considered.

Table 1: Conditions for the experiments in the narrow flume.

Run D=Deposition F=Flushing	Initial Bed Slope	Gate elevation (m)	Inflow Discharge (m^3/s)	L(m)
D1	0.0064	0.22*	0.0055	------
D2		0.22*	0.0082	------
F0	0.0031	0.11	0.0061	Wedge Shape
F1	-----	0.19	0.0055	1.15
F2		0.19	0.0065	0.88
F3		0.19	0.0048	1.35
F4		0.22	0.0064	1.5

*Bed elevation at the dam

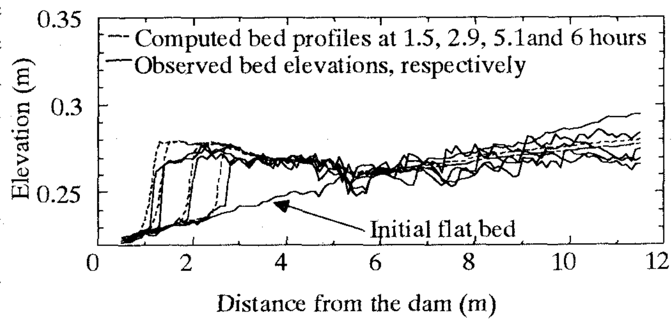

Fig. 7: Experimental and calculated results for run D1

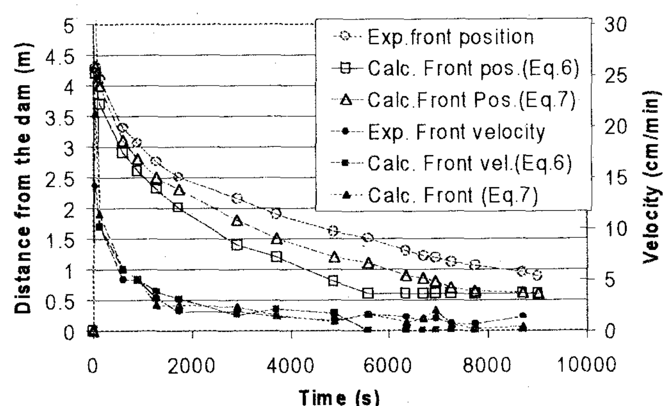

Fig. 8: Front position and displacement velocity results for run D2

c) Conditions of the experimental runs

Table 1 summarizes the conditions for each experiment. For deposition runs, two different inflow discharges were used. For flushing runs, the inflow discharge and the bottom gate elevation were varied. The value "L" represents the distance between front edge and the dam.

d) Experimental results on sediment deposition

Figure 7 shows the bed profiles for run D1. These profiles are averaged because intensive bed forms appeared. The bed aggraded rapidly producing an increase in bed elevation until certain height, afterwards the front started to grow horizontally toward the dam as time progressed.

There was minimal aggradation at the middle and tail of the front, though enough sand continued incoming from the upstream reaches. Regarding the process of front growing, it was observed how very small amounts of sediment were dragged at the front edge, falling down after reaching the edge. In this way, the front could move downstream.

It was also observed that the shallow depth (about 4 cm) produced by the aggradation, made the velocities higher enough as to keep the sediment in constant movement, so no further aggradation occurred.

Figure 8 shows the variation in time of position and displacement velocity of the front for run D2. The only significant difference between runs D1 and D2 is the velocity of front formation, which in run D2 is almost 3 times faster, this as a result of a higher inflow discharge.

The front displacement velocity diminished as the channel width increased, becomes nearly constant after 2000 secs corresponding to the time at which the front reached the wider region.

e) Experiments on hydraulic flushing

Figure 9 shows the bed and water surface transients at several instants for run F0.

The evolution of the bed and water surface transient can be easily followed from this figure. **Figure 10** shows the time variation of sediment discharge and the cumulative flushed sediment in Kgf for run F0. The value at the peak (0.44 lts$_{sed}$/s) corresponds to the average sediment discharge in the first 30 seconds. For this case, the drawdown was very fast because the initial volume of water to evacuate was small. The sediment discharge decreased gradually as time progressed and the bed profiles became less steeper.

Figure 11 shows the bed transients for flushing run F2, having a front shape as an initial bed configuration.

In this case, the first part to be eroded corresponded to the front-edge when during the drawdown, the water surface became closer to front's top (nearly 3 centimeters above) as described by Lai[5]. Then, the *local* water surface slope increased generating acceleration and maximum shear stress at the front edge and diminishing in the upstream direction and giving thereby origin to the retrogressive erosion.

Runs F1, F3 and F4 also showed similar features.

Figure 12 compares the cumulative flushed sediment weight for all flushing runs. These values were calculated from the differences in bed elevations with respect to the previously measured bed profile.

With reference to **Table 1**, it is clear that the most influencing factor is the gate elevation, so that the higher the gate location, the lower the cumulative

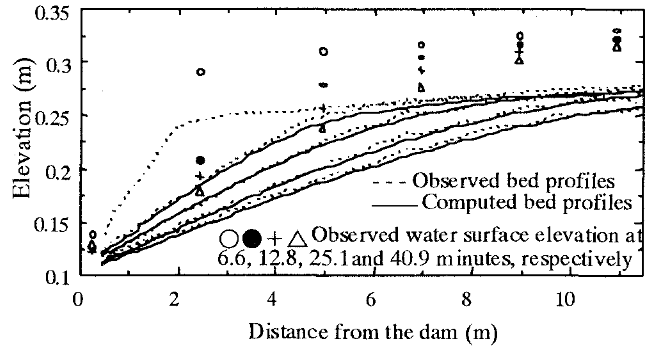

Fig. 9: Bed and water surface profiles results for run F0

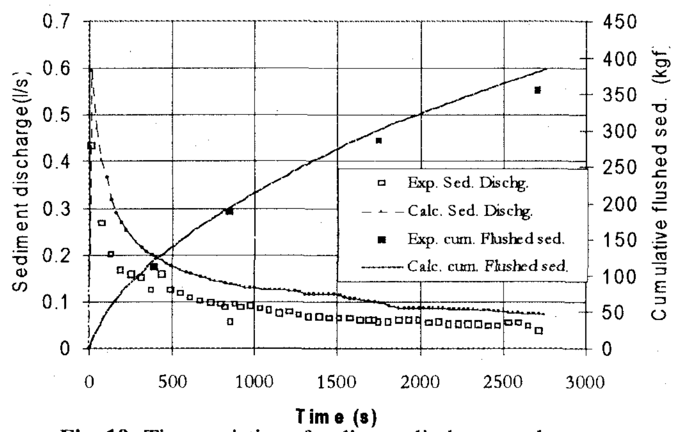

Fig. 10: Time variation of sediment discharge and cumulative flushed sediment for run F0

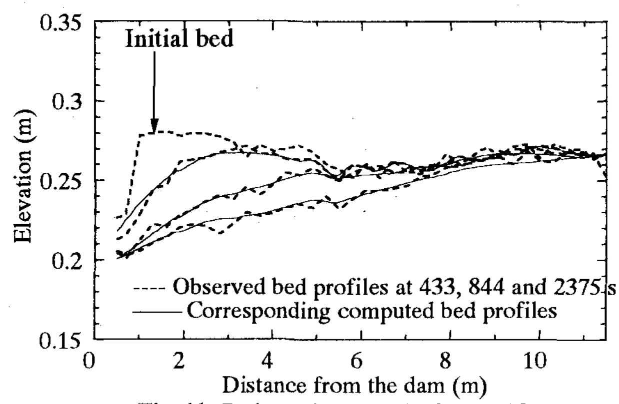

Fig. 11: Bed transients results for run F2

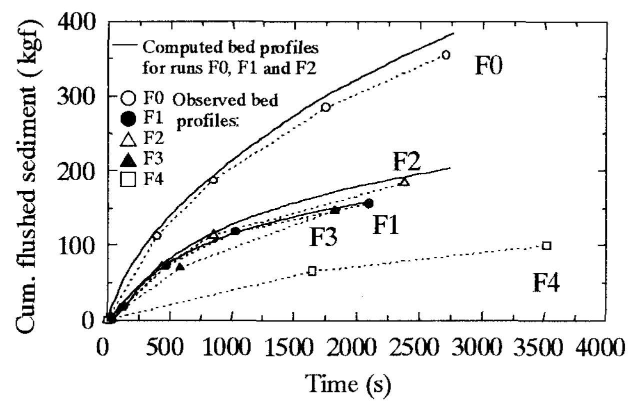

Fig. 12: Cumulative flushed sediment for all flushings.

flushed sediment and vice versa.

Regarding the effect of incoming discharge, the scouring appears to be slightly greater for larger inflow rates. That trend is clearly observed between runs F1, F2 and F3 especially in the first 1500 seconds.

f) Numerical method:

The developed model solves the Saint Venant`s equations including the effect of longitudinal change of width.

For momentum and water continuity:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (1)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial (Qv+gA\bar{h})}{\partial x}+gA(S_f-S_0)-\frac{gh^2}{2}\frac{\partial B(x)}{\partial x}=0 \qquad (2)$$

For the estimation of the bed changes the continuity equation for sediment transport is solved:

$$(1-n)\frac{\partial (z_b)}{\partial t}+\frac{1}{B(x)}\frac{\partial Q_s}{\partial x}=0 \qquad (3)$$

$$Q_s=B(x)q_s$$

The estimation of the sediment transport rate q_s is done using the Ashida-Michiue sediment transport equation:

$$\frac{q_s}{\sqrt{sgd^3}}=17\tau_{*e}^{3/2}\left[1-\frac{\tau_{*c}}{\tau_*}\right]\left[1-\frac{u_{*c}}{u_*}\right] \qquad (4)$$

In equation (4), τ_* is the non dimensional total bed shear stress, and τ_{*e} is the effective shear stress which has a lower value than τ_* when bed-forms are present. τ_{*e} is computed as:

$$\tau_{*e}=\frac{U_{*e}^{\ 2}}{sgd} \qquad (5)$$

Ashida-Michiue provided the following resistance formula to compute U_{*e}:

$$\frac{V}{U_{*e}}=6.0+5.75\log_{10}\left(\frac{R_h}{dm(1+2\tau_*)}\right) \qquad (6)$$

It was mentioned[10] that sediment transport was not computed correctly due to underestimation of resistance due to the wavy bed and wall effect.

Specifically the ratio inside the logarithmic term in equation (6) was producing very small values, therefore the computed value of U_{*e} was very high for the given average velocity, resulting in overestimation of the sediment transport.

Ashida-Michiue[1] expressed the *relative roughness* k_s as $d_m(1+\alpha\tau_*)$. In equation (6), α has a value of 2, however as they stated, the values of k_s can vary from 0.5 d_m to 4.0 d_m. So, it can be said that with the assumption of α equal to 2, only for certain range of bed-forms the sediment transport rate q_s can be predicted successfully.

According to this, it seems that for the actual experimental cases, α should be lower to improve the estimation of sediment transport.

As an alternative, the effective shear velocity was estimated using the *Einstein resistance law* equation (7) in instead of equation (6):

$$\frac{V}{U_{*e}}=\frac{V}{\sqrt{gR'_h S}}=5.75\log_{10}\left(\frac{12.27R'_h\, x}{dm}\right) \qquad (7)$$

$x = x(\delta, k_s)$, δ : boundary layer thickness

in this case $k_s = d_m$

Equations (6) and (7) are very similar, but equation (7) is in terms only of the average velocity V, the sediment size $k_s = d_m$ and the hydraulic radius related to the skin friction R'_h. The use of "total" variables like total shear stress τ_*, total hydraulic radius R_h is avoided, which is preferable because these values have lumped the effect of the walls and bed forms, which are not related directly with the sediment transport.

The following computed results were obtained using the combination of equations (4) and (7); unless otherwise stated.

The method of finite differences using the predictor-corrector MacCormack scheme was implemented. The nodes interval for computation was made equal to 10 cm, thereby coinciding with the pitch used to measure the bed profiles in the laboratory experiments.

Regarding the boundary conditions for deposition runs (sub-critical flow), discharge was specified at the upstream end and water surface elevation at the downstream end. For the sediment continuity equation, at the upstream end the non-equilibrium sediment transport equation developed by Fukuoka et al.[4] was adopted to estimate the incoming sediment discharge and at the downstream end the bed elevation was specified.

For flushing runs (supercritical flow), discharge and water surface elevation were provided at the upstream end. For sediment continuity, the same boundary conditions used for deposition runs were adopted. The value of Manning's n allowing the fitting of the observed water surface elevation profiles was found to be 0.0135.

Figure 7 shows the results after calibration using run D1, the front's shape, height and displacement velocity were reasonably well fitted. Later, the model was validated by applying it to run D2 for which the computed front displacement velocity was greater than the observed, but closer than the case computed using the traditional method using Ashida-Michiue resistance formula (eq.6). This is shown in **Figure 8**.

Both cases, using eqs. (6) or (7) gave overestimation of the front growth. A possible reason is that in the laboratory experiment, the presence of larger bed forms in comparison to run D1 (lower discharge and depth) limited even more the actual sediment transport rate.

For the flushing process the model calibration was done using the experimental data of run F0. The results are shown in **Figures 9** and **10**, the bed profiles fitted reasonably well with the experimental data; though the computed sediment discharge and cumulative flushed sediment were somewhat overestimated, but in general the process is well represented. The model was compared with the experimental data of runs F1 and F2. **Figure 11** shows the computed bed profiles for run F2 which are in agreement with the observed data, similar agreement was observed for run F1. Finally in **Figure 12** the computed cumulative flushed sediment weight in units of Kgf for runs F0, F1 and F2 is presented.

According to the evaluation results, it can be said that with relatively simple numerical models, these processes can be predicted when they have a strong one-dimensional character.

CONCLUSIONS:

From the results, the following conclusions were obtained:

a) It was understood that the water surface elevation limits the aggradation during the deposition process driving the front to develop mainly horizontally.

b) The mechanism of retrogressive erosion during water surface drawdown was clarified. The relative importance of factors like bottom gate elevation and inflow discharges was understood.

c) The one-dimensional unsteady movable model tends to overestimate the sediment transport, due to the inability to predict the resistance related to the skin friction and the random appearance of bed-forms in the experiments.

d) Even though, both processes were well described so that the model still is a good tool for prediction of both processes under different conditions and can be used for preliminary estimation of deposition and flushing operations provided that bed-load contributions are predominant in the formation of the deposits.

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REFERENCES:

1) Ashida, K and Michiue, M.: Study on hydraulic resistance and bed-load transport rate in alluvial streams. Proceedings of the Japanese Society of Civil Engineers. No 206, pp.59-69, October 1972.

2) Bhallamudy, M. and Chaudry, H.: Numerical modeling of aggradation and degradation in alluvial channels. Journal of Hydraulic Engineering. ASCE.Vol 117,pp 1145-1163, September 1991.

3) Chaudry, H.: Open channel flow. Prentice Hall. Inc. A. Simon & Schuster Co. New Jersey.,Chapters 14 and 15, 1993

4) Kim; Fukuoka, Shoji and Yamasaka, M.: Determination of the parameter Kb in the non-equilibrium sediment transport formula. Proceedings of the 38th Annual Conference of the Japan Society of Civil Engineers. Pp539-540,1983

5) Lai, J.: Hydraulic flushing for reservoir desiltation. Doctoral Thesis at University of California, at Berkeley. UMI Dissertation Services, 1994.

6) Morris, G and Fan, J.: Reservoir sedimentation handbook: Design and management of dams, reservoirs and watersheds for sustainable use. McGraw-Hill Companies, Inc., Chapter 2, 1998.

9) Shen, H.; Lai J.: Hydraulic desiltation for non-cohesive sediment. Hydraulic Engineering'93, ASCE, pp 119-123, 1993.

10) Masis, Julio; Fukuoka, Shoji; Watanabe Akihide and Uo Kazuki.: Experimental and Numerical Simulation of Deposition and Sediment Flushing Processes in Reservoirs. 55th Annual Conference of the Japanese Society of Civil Engineers. In CD-ROM Presentation II-256, Set 2000.

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